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User's Manual for FEMOM3DS Version 1.0

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CONTENTS

1. INTRODUCTION

FEMOM3DS is a computer code written in FORTRAN 77 to compute electromagnetic(EM) scattering characteristics of a three dimensional object with complex materials (figure 1) using combined Finite Element Method (FEM)/Method of Moments (MoM) technique[1]. This code uses the tetrahedral elements, with vector edge basis functions for FEM in the volume of the cavity and the triangular elements with the basis functions similar to that described in [2], for MoM at the outer boundary. By virtue of FEM, this code can handle any arbitrarily shaped three-dimensional cavities filled with inhomogeneous lossy materials. The basic theory implemented in the code is given in Appendix 1.

The User's Manual is written to make the user acquainted with the operation of the code. The user is assumed to be familiar with the FORTRAN 77 language and the operating environment of the computers on which the code is intended to run. The organization of the manual is as follows. Section 1 is the introduction. Section 2 explains the installation requirements. The operation of the code is given in detail in Section 3. Two example runs, the first EM scattering characteristics of a dielectric sphere and the second EM scattering characteristics form an inlet cavity are demonstrated in Section 4. Some test cases are presented in Section 5 to show the flexibility of the code. The test cases were run by the authors to validate the code. Users are encouraged to try these cases to get themselves acquainted with the code.

2. INSTALLATION OF THE CODE

The distribution disk of FEMOM3DS is 3.5" floppy disk formatted for IBM compatible PCs. It contains a file named `femom3ds.tar.gz`. This file has to be transferred to any UNIX machine via `ftp` using binary mode. On the UNIX machine, use the following commands to get all the files.

```
gunzip femom3ds.tar.gz
tar -xvf femom3ds.tar
```

This creates a directory `FEMOM3DS-1.0`, which in turn contains the

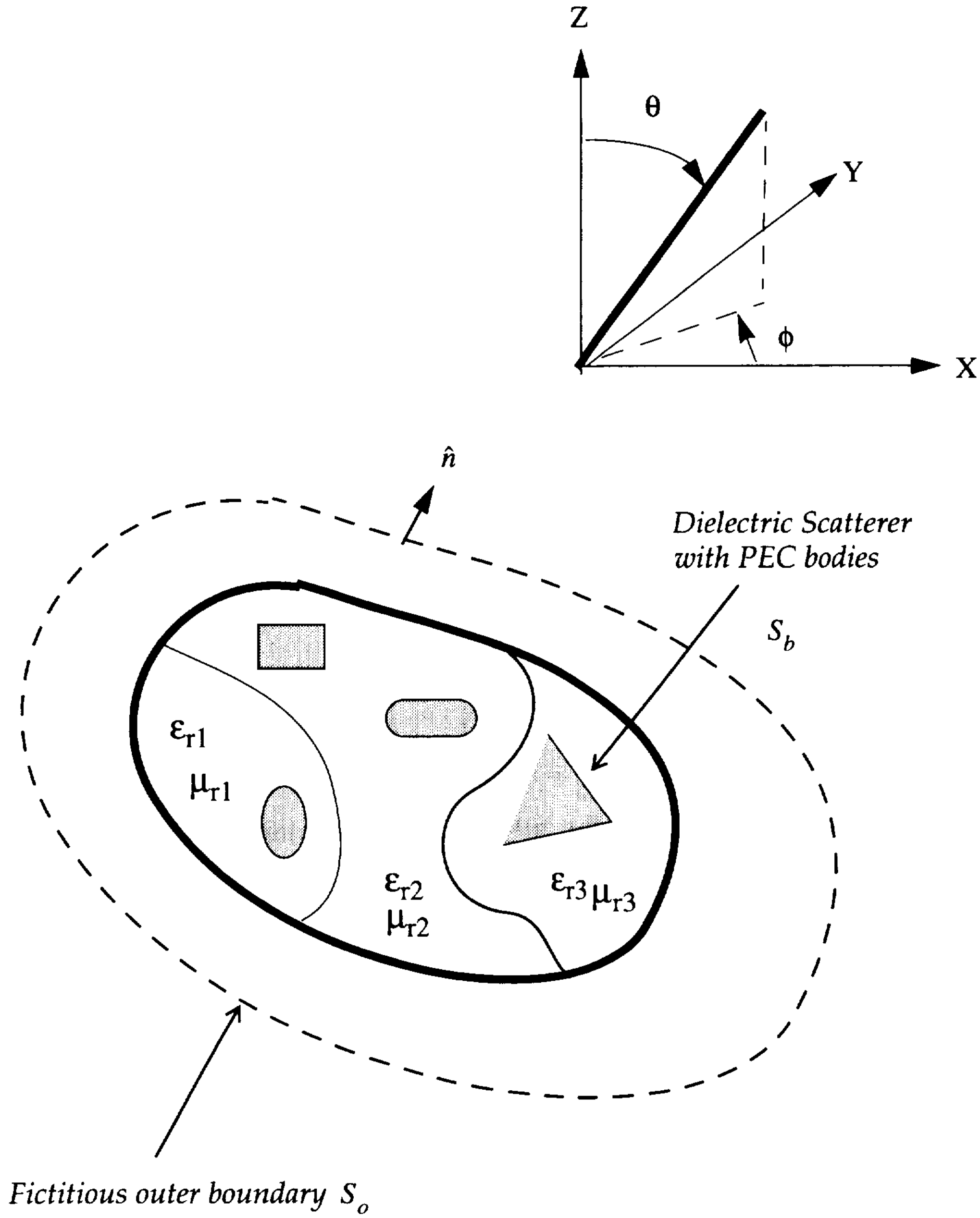


Figure 1 Illustration of the scattering body with surface, S_b enclosed by a fictitious outer surface S_o, which is used to terminate the FEM compuatational domain.

subdirectories, `FEMOM3DS` (source files for the main code), `PRE_FEMOM3DS` (source files for preprocessing code), `Example1` `and` `Example2.` As the code is written in FORTRAN 77, with no particular computer in mind, the source code in these directories should compile on any computer architecture without any problem. The code was successfully complied on a CONVEX machine, and the compilation can be done by using a `makefile` file for the different machines such as SUN, SGI etc. The complete listing of the directories in the distribution disk is given in Appendix 2.

3.0 OPERATION OF THE CODE

The computation of EM scattering characteristics from a specific geometry with FEMOM3DS is a multi-stage process as illustrated in figure 2. The geometry of the problem has to be constructed with the help of any commercial Computer Aided Design (CAD) package. In our case, we used COSMOS/M[3] as our geometry modeler and meshing tool. Once the object geometry is modelled, PEC surfaces are to be identified for implementing proper boundary conditions. As FEMOM3DS uses edge based basis functions, the nodal information supplied by most of the meshing routines cannot be readily used. Hence, a preprocessor PRE_FEMOM3DS is written to convert the nodal based data into edge based data and then is given as input to FEMOM3DS. For the convenience of the users, who use different CAD/meshing packages other than COSMOS/M, PRE_FEMOM3DS accepts the nodal based data in a generic format also. The procedures involved for using COSMOS/M input data file or generic input data file are explained below.

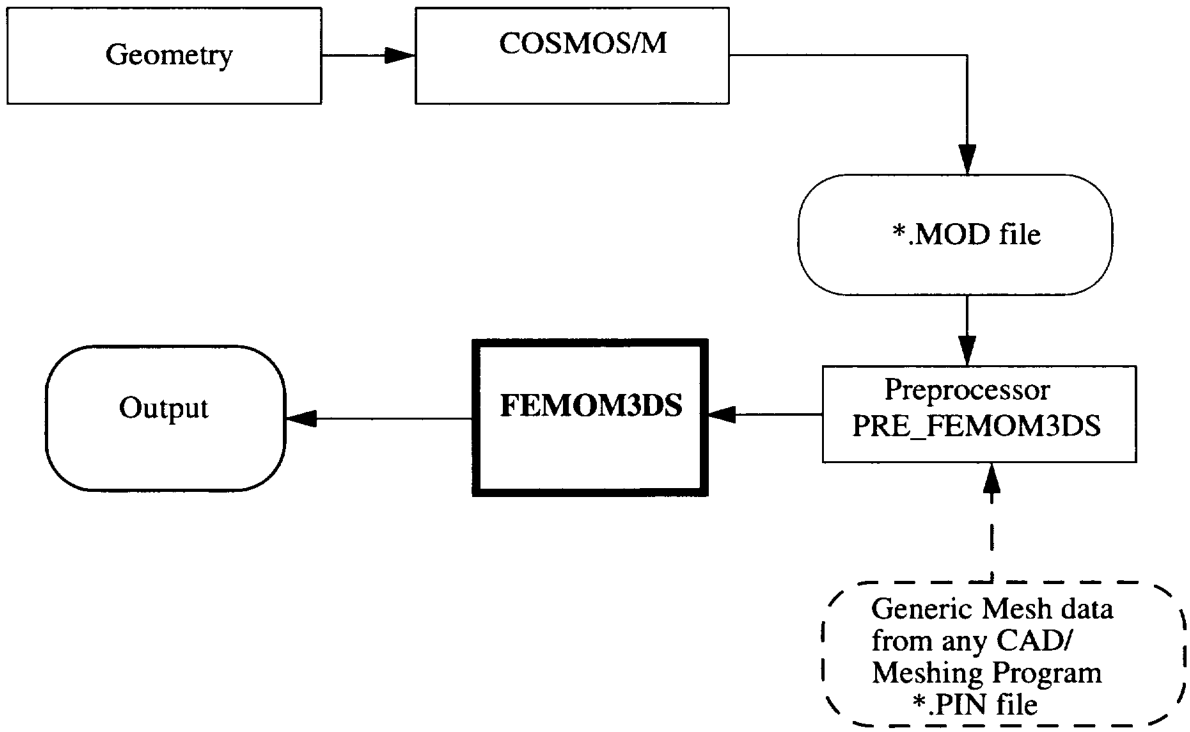


Figure 2 Flow chart showing the various steps involved in using FEMOM3DS

With the help of COSMOS/M, the geometry is constructed and meshed with tetrahedral elements. The user is assumed to be familiar with COSMOS/M package and its features. Once the mesh is generated, one needs to identify the following to impose proper boundary conditions:

(a) tetrahedral elements with different material parameters[1],

(b) elements on PEC surfaces

(c) elements on the outer boundary (for the purpose of calculating the electric current)

This is done using the available features in COSMOS/M. Sample *.SES files of COSMOS/M which illustrate these features are given in Appendix 3. Finally the *.MOD file is generated with the required mesh information. PRE_FEMOM3DS accepts the *.MOD file as input and generates the required edge based data.

For users, who can do geometry modelling and meshing of the model with any other CAD package, the nodal based information is required to be placed in a file `problem.PIN`,

1. COSMOS/M has a feature by which it can group tetrahedral elements with different material properties into different groups. For a generic file input, the user has to specify the material property index for each tetrahedral element to indicate its material property group(see Appendix 4).

where *problem* is the name of the problem under consideration. The format required for `*.PIN` file is given in Appendix 4. Note that all the dimensions of the geometry are assumed to be in centimeters.

The PRE_FEMOM3DS code gives the following prompts:

```
pre_femom3ds
Give the problem name:
```

The problem name is the user defined name for the particular problem under consideration.

```
COSMOS file (1) or GENERIC (2) file?
```

If you are using *.MOD file from COSMOS/M, give 1 or using the generic input data file explained above, give 2.

PRE_FEMOM3DS generates the following files with required edge based information.

(a) *problem*_nodal.dat - Node coordinates and the node numbers for each element

(b) *problem*_edges.dat - Information on edges, such as nodes connecting each edge, etc.

(c) *problem*_surfed.dat - Information on number of edges on each surface

(d) *problem*.POUT - General information on the mesh.

The files (a) to (c) are used as input for FEMOM3DS. Users need not interact or modify the above files.

After PRE_FEMOM3DS is run, all but one input data file required for FEMOM3DS are ready. FEMOM3DS expects to find *problem*.MAT file which contains the material constants information required for the volume elements. The format of the *problem*.MAT is as given below:

N_g, Maximum number of material groups

$\varepsilon_{r1}, \mu_{r1}$ Complex relative permittivity, complex relative permeability respectively

$\varepsilon_{r2}, \mu_{r2}$ for material groups 1, 2, 3, ..., N_g

.

.

$\varepsilon_{rN_g}, \mu_{rN_g}$

In the PRE_FEMOM3DS, all the terahedral elements are given the material group index. The material parameters given in *problem*.MAT are read into FEMOM3DS and the proper material parameters are assigned to each tetrahedral element according to its material property index. Once the *problem*.MAT is ready, FEMOM3DS code can be run. The FEMOM3DS code gives the following prompts:

```
femom3ds
Give the problem name :
```

This name should be the same as given for PRE_FEMOM3DS

```
Frequency (GHZ) :
```

This is the frequency of operation. If the dimensions of the problem are in wavelengths, frequency should be specified as 30 GHz as FEMOM3DS assumes that all dimensions are in centimeters.

```
Monostatic or Bistatic ?
 Give 1 for Monostatic, 2 for Bistatic
```

This is to specify whether to calculate monostatic electromagnetic scattering or bistatic electromagnetic scattering. In the case of monostatic scattering the observation point is in the same direction as that of the incident wave, whereas in the biscattering case, the direction of the incident wave is fixed and the EM scattering is observed at different directions. Hence one has to specify the direction of the incident wave for bistatic scattering.

For Bistatic scattering

```
Incident angles, theatai(degs), phii(degs)
```

θ_i and ϕ_i give the direction of the incident plane wave.

```
Give 0 for H-polarization
Give 90 for E-polarization
```

This is to specify the polarization of the incident plane wave.

```
Plane of incidence-
Give 1 for fixed phi and phi(degs)
     2 for fixed theta and theta(degs)
```

This specifies the angle of incidence for the incident wave. Backscatter calculations can be done at a constant ϕ-plane or at a constant θ-plane by choosing either 1 or 2 and giving the value of ϕ or θ at the plane of interest respectively.

```
Give angle of incidence-
start,end,increment (degs) :
```

This specifies range of angles for which backscatter calculations are to be performed. For a constant ϕ-plane, these are values of θ and for constant θ-plane these are values of ϕ.

FEMOM3DS generates the file *problem*.OUT, which contains information on CPU times for matrix generation, matrix fill, the parameters for electromagnetic scattering data. FEMOM3DS also generates another file *problem*_bicgd.DAT which contains information on convergence history of diagonally preconditioned biconjugate gradient algorithm used to solve the matrix equations.

4.0 SAMPLE RUNS

Two example runs are illustrated in this section. They are selected to illustrate some of the features of FEMOM3DS.

Example 1 : Bistatic Scattering from a dielectric sphere

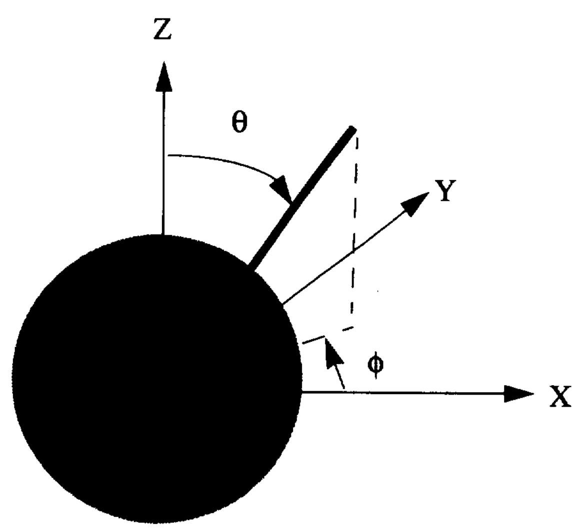


Figure 3 Dielectric sphere of radius 0.16cm with $\varepsilon_r = \mathit{4.0}, \mu_r = \mathit{1.0}$

A dielectric sphere of radius 0.16cm, with $\varepsilon_r = 4.0$ and $\mu_r = 1.0$. Bistatic scattering is calculated with the plane wave incident from the direction $\theta = 180^o$ and $\phi = 0^o$.

First the PRE_FEMOM3DS

```
cjr@magellan:{37} pre_femom3ds
 Give the problem name :
sp
 COSMOS file(1) or GENERIC(2) file ? :
1
  Opening file :sp.MOD
  Nodes=          52
  No of elements=        135

 Read the following data
 Nodes=          52
 Elements=         135
 Elements on surface 1=          88
  Max number of material groups=          1

 Forming the edges !!! Be patient !!!

 Number of edges=         230
  Order of the FEM matrix- nptrx=        230

 **************************************************

 Number of nodes=          52
 Number of elements=         135
 Number of total edges=         230
 Number of elements on Surface 1=          88
 Number of edges on surface 0(pec)=          0
 Number of edges on surface 1=        132
 Max number of maetrial groups=          1


 **************************************************
STOP:
```

The `sp.MAT` file for this problem is given below:

```
1
(4.0,0.0) (1.0,0.0)
```

And then FEMOM3DS :

```
 Give the problem name :
sp
 Fequency (GHZ) :
30.0
 Monostatic or Bistatic ?
 Give 1 for Monostatic, 2 for Bistatic
2
 Incidence angles, theatai(degs),phii(degs)
180.0 0.0
 Give 0 for H-polarization
 Give 90 for E-polarization
0.0

  Plane of incidence/obsr(Mono) - Obser(Bi)-
 Give 1 for fixed phi and phi(deg)
      2 for fixed theta and theta(degs)
1 0
  Give angle of incidence/obsr(Mono)- obsr(Bi):
 start, end, increment
0 180 10
  Reading the input !!
 Finished reading the data
 Order of the FEM matrix-net=        230
 Total matrix order=net1=net+nsptrx1=        362

 Order of the MoM matrix, nsptrx1=        132
 ***************************************
 *                                     *
 *                                     *
 *        FEMoM3DS(Version 1.0)        *
          Problem : sp
 *                                     *
 *                                     *
 ***************************************

 BiSTATIC RADAR CROSS SECTION

 Frequency (GHz)          =   30.00000
 Order of the FEM-MoM matrix=      362
 Order of the MoM matrix    =      132

 Incident Angles
   Thetai(degs)=   180.0000
   Phii(degs)  =          0.
```

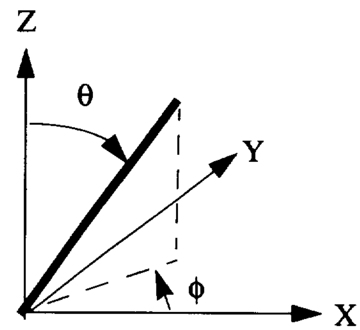
```
H-Polarization
Sweep through theta : phi =          0
Start(degs)=          0
Stop(degs) =        180
Increment(degs)=          10
 Number of non zeros in amat(zmatrices)=        2924
Time to fill FEM matrix=  0.1569319
 Zmatrixeh
Time to fill zmatrixeh=  6.2719822E-02
 Non zeros after zmateh=       3584
zmatrixej
Time to fill zmatrixej=   22.97427
 Non-zeros after zmatej=      21008
zmatrixem
Time to fill zmatrixem=   30.85342
Time to fill zmatrices (secs)=   53.89322
Total no of non zeros after adding zmatrices=       38432
CONVERGENCE ACHIEVED in          282 iterations
Residual Norm=  5.5933034E-04
 Solution time(secs)=   33.03685
```

Ang(deg)	SigHH(dB)	SigHE(dB)
0	-9.876550	-58.94287
10	-10.01219	-59.61543
20	-10.43050	-60.21722
30	-11.14991	-60.79119
40	-12.20645	-61.43825
50	-13.66489	-62.27667
60	-15.64468	-63.39064
70	-18.38787	-64.75037
80	-22.48750	-66.08037
90	-30.15921	-66.86278
100	-37.94263	-66.89146
110	-26.00531	-66.64410
120	-21.50988	-66.69263
130	-18.91976	-67.33405
140	-17.24439	-68.63268
150	-16.12831	-70.31013
160	-15.40722	-71.30753
170	-14.99740	-70.54909
180	-14.85810	-68.86301

```
*---------------------------------------------------*
```

The complete session of this run on a CONVEX C-220 along with all the files is kept in the directory `/FEMOM3DS-1.0/Example1`.

Example 2: Monostatic Scattering from a rectangular inlet cavity



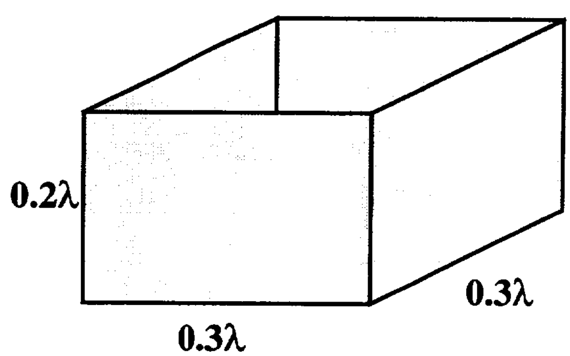


Figure 4 Rectangular inlet cavity

The geometry of the rectangular inlet cavity is shown in figure 3. The cavity is open on one end and is closed at the bottom. Monostatic scattering is calculated.

First the PRE_FEMOM3DS

```
 Give the problem name :
inlet
 COSMOS file(1) or GENERIC(2) file ? :
1
  Opening file :inlet.MOD
  Nodes=         101
  No of elements=         283
```

```
 Read the following data
 Nodes=         101
 Elements=         283
 Elements on surface 1=         160
  Max number of material groups=           1

 Forming the edges !!! Be patient !!!

 Number of edges=         463
  Order of the FEM matrix- nptrx=         263

 ***************************************************

 Number of nodes=         101
 Number of elements=         283
 Number of total edges=         463
 Number of elements on Surface 1=         160
 Number of edges on surface 0(pec)=         200
 Number of edges on surface 1=         240
 Max number of maetrial groups=           1


 ***************************************************
STOP:
```

The `inlet.MAT` file for this problem is given below:

```
1

(1.0,0.0) (1.0,0.0)
```

And then FEMOM3DS :

```
 Give the problem name :
inlet
 Fequency (GHZ) :
30.0
 Monostatic or Bistatic ?
 Give 1 for Monostatic, 2 for Bistatic
1

 Give 0 for H-polarization
 Give 90 for E-polarization
0

  Plane of incidence/obsr(Mono) - Obser(Bi)-
 Give 1 for fixed phi and phi(deg)
```

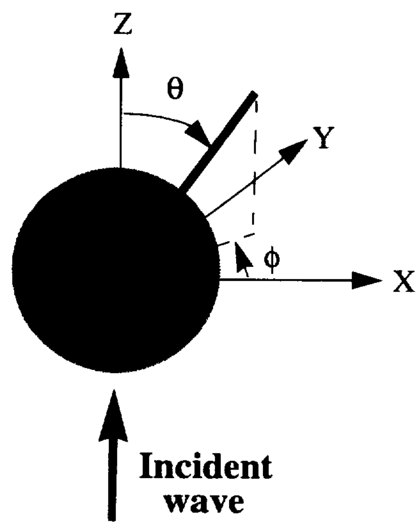
```
      2 for fixed theta and theta(degs)
1 0
  Give angle of incidence/obsr(Mono)- obsr(Bi):
 start, end, increment
0 180 10

  Reading the input !!
 Finished reading the data
 Order of the FEM matrix-net=         263
 Total matrix order=net1=net+nsptrx1=           503

 Order of the MoM matrix, nsptrx1=         240

 ***************************************
 *                                     *
 *                                     *
 *        FEMoM3DS(Version 1.0)        *
          Problem : inlet
 *                                     *
 *                                     *
 ***************************************

 MONOSTATIC RADAR CROSS SECTION

 Frequency (GHz)            =   30.00000
 Order of the FEM-MoM matrix=         503
 Order of the MoM matrix    =         240
 H-Polarization
 Sweep through theta : phi =          0
 Start(degs)=           0
 Stop(degs) =         180
 Increment(degs)=          10
  Number of non zeros in amat(zmatrices)=          3179
 Time to fill FEM matrix=  0.2643120
  Zmatrixeh
 Time to fill zmatrixeh=  7.8801036E-02
  Non zeros after zmateh=        3379
 zmatrixej
 Time to fill zmatrixej=   79.19982
  Non-zeros after zmatej=       60979
 zmatrixem
 Time to fill zmatrixem=   48.21815
 Time to fill zmatrices (secs)=   127.4995
 Total no of non zeros after adding zmatrices=         70579
```

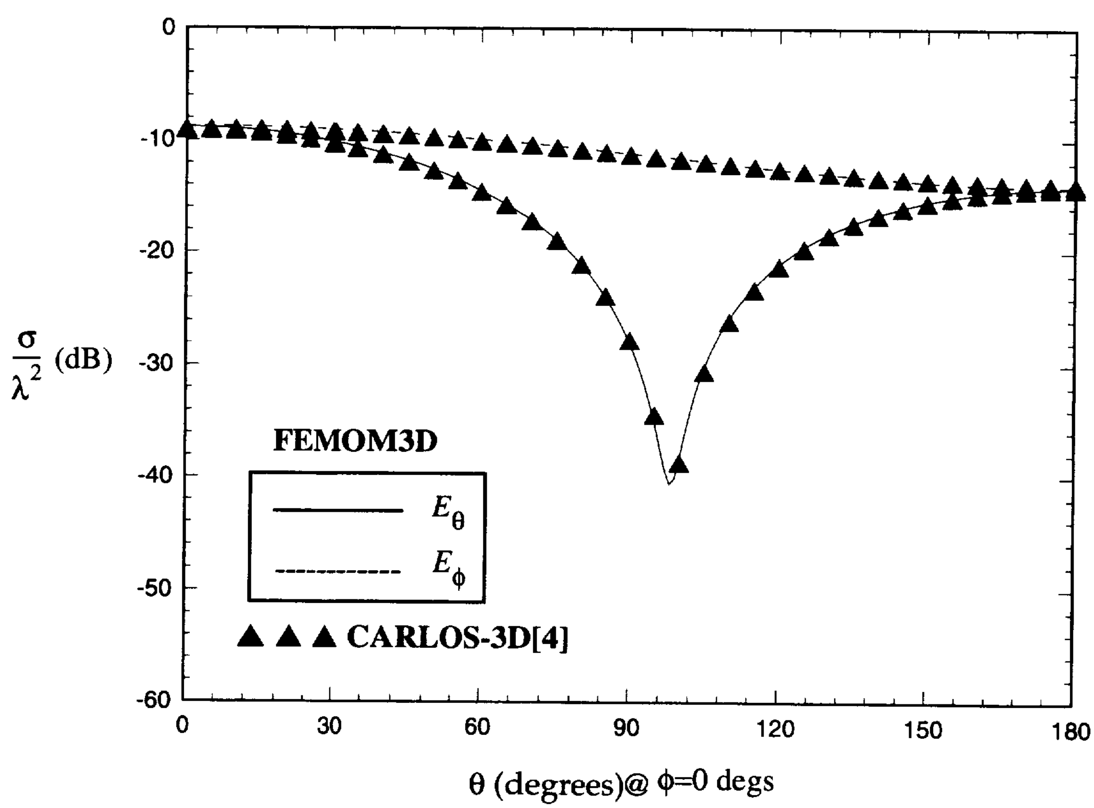
```
Ang(deg)   SigHH(dB)        SigHE(dB)        Time(secs)

     0 -0.3081026        -55.40033        67.74269
    10 -0.4520388        -52.60987        60.19102
    20 -0.9098186        -49.97753        57.31442
    30  -1.734988        -47.91700        54.19781
    40  -2.999914        -46.49533        55.80737
    50  -4.769355        -45.82520        53.95328
    60  -7.047320        -45.95884        54.81299
    70  -9.630483        -46.89593        63.12811
    80  -11.76193        -48.70896        58.05768
    90  -12.20721        -51.62140        55.32001
   100  -10.86643        -55.89311        66.16351
   110  -8.766810        -59.68416        57.74194
   120  -6.633481        -57.03788        68.58752
   130  -4.791438        -53.42066        56.93665
   140  -3.356782        -50.92786        59.78656
   150  -2.333028        -49.05974        54.35376
   160  -1.669239        -47.60739        57.40320
   170  -1.302017        -46.63602        63.49841
   180  -1.183381        -46.32928        55.77466

*---------------------------------------------------------*
```

The complete session of this run on a CONVEX C-220 along with all the files is kept in the directory `./FEMOM3DS-1.0/Example2`.

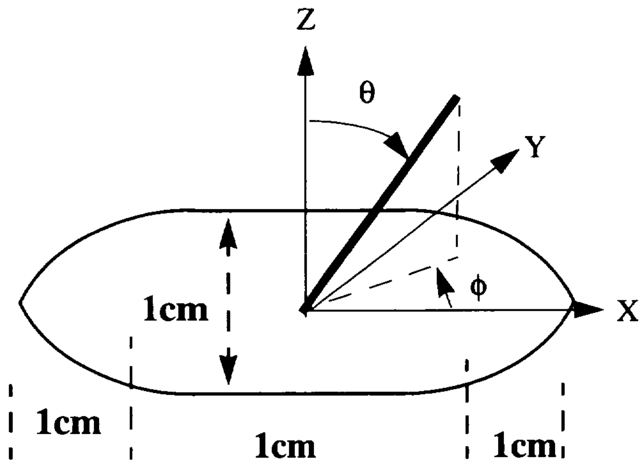
5.0 TEST CASES

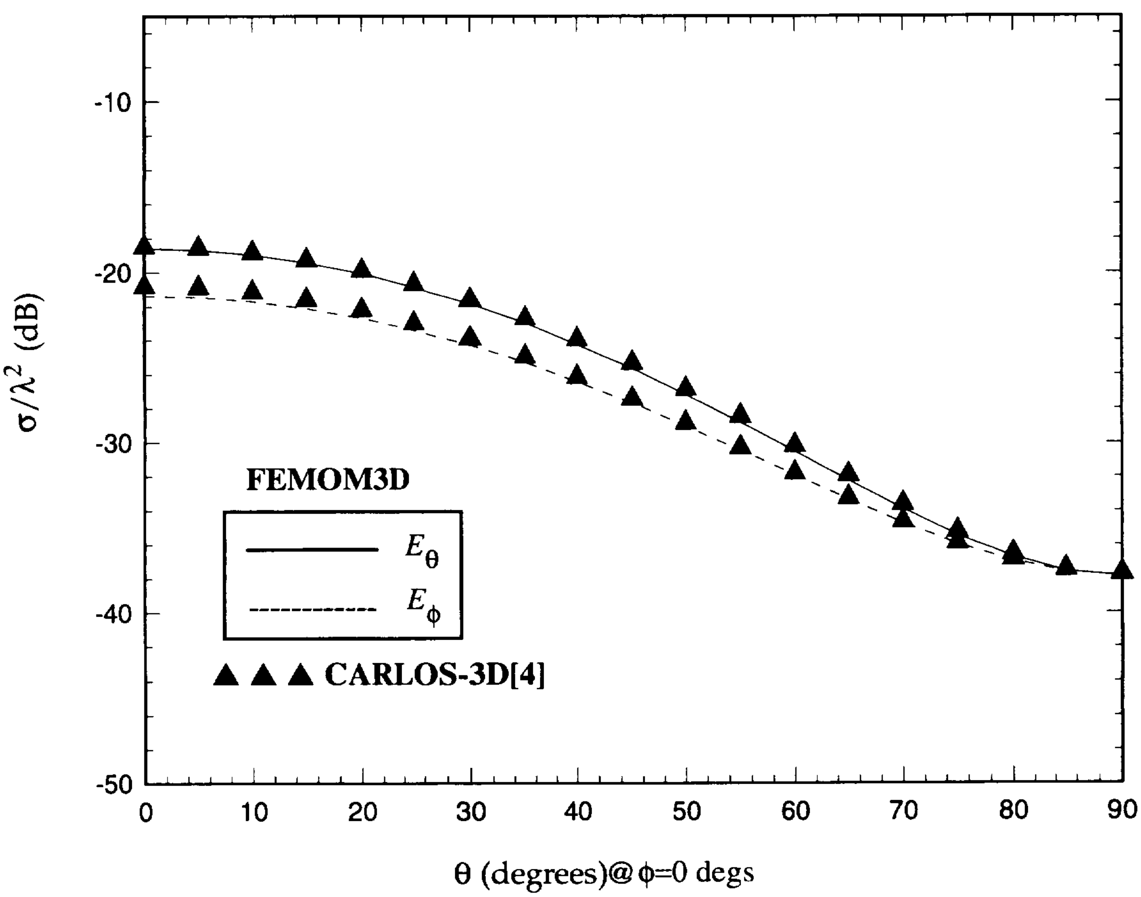
Test Case 1: Bistatic RCS of a dielectric sphere ; (ka=1, ε_r=4.0, θ_{in}=180°, ϕ_{in}=0°)



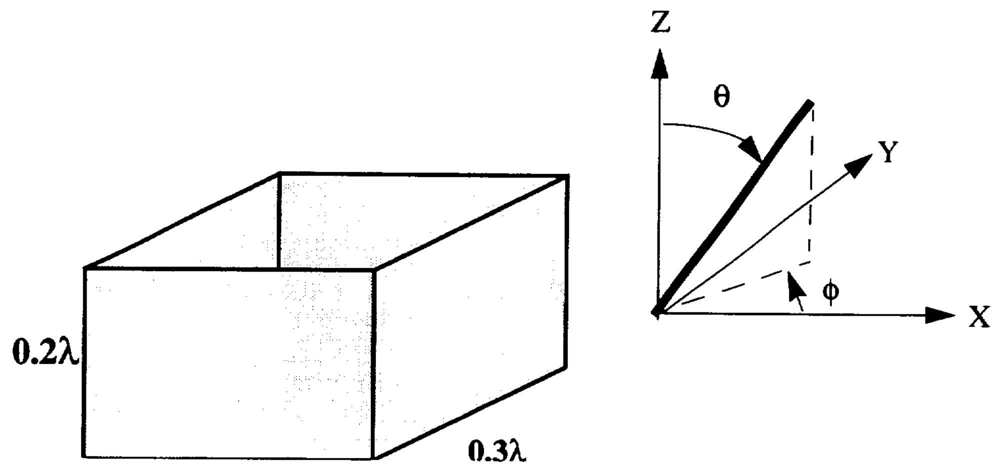


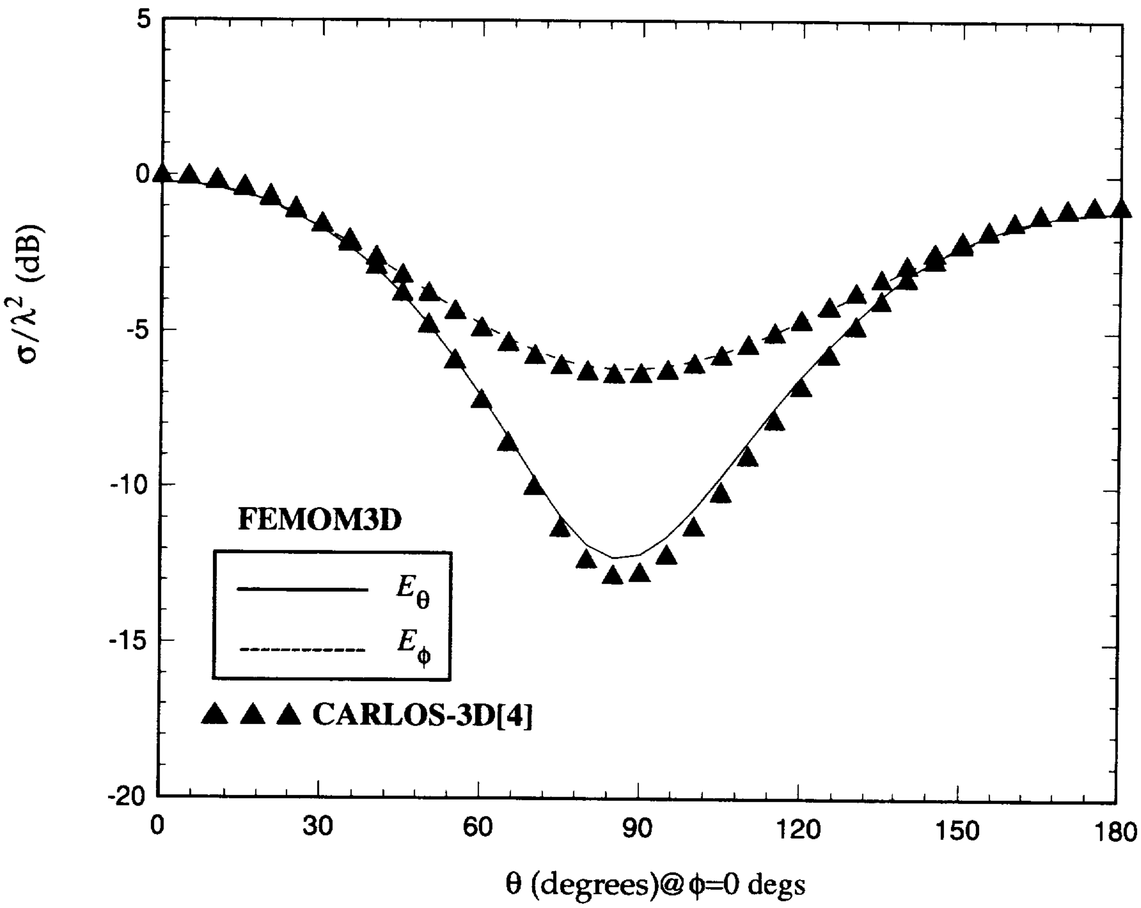
Test Case 2: Monostatic RCS of a dielectric ogive ; (Freq=6.0GHz, ε_r=2.0)





Test Case 3 : Monostatic RCS of a rectangular inlet cavity with opening on one side





6.0 CONCLUDING REMARKS

The usage of FEMOM3DS code is demonstrated so that the user can get acquainted with the details of using the code with minimum possible effort. As no software can be bug free, FEMOM3DS is expected to have hidden bugs which can only be detected by the repeated use of the code for a variety of geometries. Any comments or bug reports should be sent to the authors. As the reported bugs are fixed and more features added to the code, future versions will be released. Information on future versions of the code can be obtained from

Electromagnetics Research Branch (MS 490)
Flight Electronics and Technology Division
NASA-Langley Research Center
HAMPTON VA 23681

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Appendix 1

Theory for FEMOM3DS

This appendix is intended to give a brief description of the theory behind the code. The geometry of the structure to be analyzed is shown in figure 1. S_b represents the outer surface of the 3D object, S_o represents the area of the fictitious outer boundary to be used for terminating the FEM computational domain. The electric field inside the compuational domain satisfies the vector wave equation[5]

$$\nabla\times\left(\frac{1}{\mu_r}\nabla\times\mathbf{E}\right)-k_o^2\varepsilon_r\mathbf{E} = 0 \tag{1}$$

where ε_r and μ_r are the relative permittivity and relative permeability of the medium. The time dependency of $\exp(j\omega t)$ is assumed through out this report. To facilitate the suitable solution of the partial differential equation in (1) via FEM, multiply equation (1) with a vector testing function $\mathbf{T}$ and integrate over the volume of the computational domain. By applying suitable vector identities, equation(1) can be written in its weak form as,

$$\iiint_V \frac{1}{\mu_r}(\nabla\times\mathbf{T})\bullet\left(\frac{1}{\mu_r}\nabla\times\mathbf{E}\right)dv-k_o^2\varepsilon_r\iiint_V\mathbf{T}\bullet\mathbf{E}dv = \iiint_V\nabla\bullet\left(\mathbf{T}\times\frac{1}{\mu_r}\nabla\times\mathbf{E}\right)dv \tag{2}$$

Applying the divergence theorem to the right hand side of equation(2), the volume integral is written as the surface integral over the surface S_o terminating the FEM computational domain.

$$\iiint_V \frac{1}{\mu_r}(\nabla\times\mathbf{T})\bullet(\nabla\times\mathbf{E})\,dv-k_o^2\varepsilon_r\iiint_V\mathbf{T}\bullet\mathbf{E}dv = -\iint_{S_o}\mathbf{T}\bullet\left(\hat{n}\times\frac{1}{\mu_r}\nabla\times\mathbf{E}\right)ds \tag{3}$$

where $\hat{n}$ is the unit outward normal to the surface S_o.

To discretize the above volume and surface integrals, the FEM computational domain is subdivided into small volume tetrahedral elements. The electric field is expressed in terms of vector edge basis functions[2] which enforce the divergenceless condition of the electric field implicitly

$$\mathbf{E} = \sum_{i=1}^{6} e_i\mathbf{W}_i \tag{4}$$

where e_i's are the unknown coefficients associated with each edge of the tetrahedral element and $\mathbf{W}_i$'s are the basis functions and are given in detail in [6]. The testing function $\mathbf{T}$ is taken to be the same set of basis functions as given in equation (4), i.e.,

$$\mathbf{T} = \mathbf{W}_j \qquad j=1,2,3,4,5,6 \tag{5}$$

The discretization of the FEM computational volume automatically results in discretization of surface S_o in triangular elements. The evaluation of the surface integrals over the outer boundary is evaluated either by using Method of Moments(MoM) or Absorbing Boundary Conditions (ABCs).

Evaluation of surface integral over S_o - MoM formulation :

At the fictitious outer boundary the electric field is subjected to the condition that the fields are continuous across the boundary, i.e.,

$$\mathbf{E}\big|_{at\ S_o^+} = \mathbf{E}\big|_{at\ S_o^-} \tag{6}$$

where S_o^+ denotes the outer side of S_o and S_o^- denotes the inner side of S_o. The electric field $\mathbf{E}\big|_{at\ S_o^-}$ is the field quantity being evaluated in the computational volume through FEM. The electric field ouside S_o is evaluated explicitly using the following equation[5, eq.3-83]:

$$\mathbf{E}\big|_{at\ S_o^+} = -\nabla\times\mathbf{F} - j\omega\mu_o\mathbf{A} + \frac{1}{j\omega\mu_o}\nabla\nabla\bullet\mathbf{A} + \mathbf{E}_{inc} \tag{7}$$

where

$$\mathbf{A} = \text{Magnetic Vector Potential} = \frac{1}{4\pi}\iint_{S_o}\frac{\mathbf{J}\exp\left(-jk_o|\mathbf{r}-\mathbf{r}_o|\right)}{|\mathbf{r}-\mathbf{r}_o|}ds \tag{8}$$

$$\mathbf{F} = \text{Electric Vector Potential} = \frac{1}{4\pi}\iint_{S_o} \frac{\mathbf{M}\exp\left(-jk_o|\mathbf{r}-\mathbf{r}_o|\right)}{|\mathbf{r}-\mathbf{r}_o|}ds \tag{9}$$

and

$$\mathbf{E}_{inc} = \text{Incident Electric Field} = \mathbf{E}_i \exp\left[j\left(k_x x + k_y y + k_z z\right)\right]$$

where

$$\mathbf{E}_i = \hat{x}E_{xi} + \hat{y}E_{yi} + \hat{z}E_{zi} \tag{10}$$

and

$$E_{xi} = \cos\theta_i \cos\phi_i \cos\alpha - \sin\phi_i \sin\alpha \tag{11}$$

$$E_{yi} = \cos\theta_i \sin\phi_i \cos\alpha + \cos\phi_i \sin\alpha \tag{12}$$

$$E_{zi} = -\sin\theta_i \cos\alpha \tag{13}$$

$$k_x = k\sin\theta_i \cos\phi_i \tag{14}$$

$$k_y = k\sin\theta_i \sin\phi_i \tag{15}$$

$$k_z = k\cos\theta_i \tag{16}$$

$\mathbf{J}$ and $\mathbf{M}$ are assumed to be equivalent electric and magnetic currents respectively at the outer surface S_o. θ_i and ϕ_i indicate the direction of the incident field. The terms with the magnetic vector potential contribute to the electric field outside V due to the equivalent electric current radiating into free space. Similarly the term with electric vector potential contribute to the electric field outside V due to the equivalent magnetic current radiating into free space(figure 5).

Substituting equation (7) into equation (6) and multiplying by a testing function $\hat{n} \times \mathbf{T}$ on both sides and integrate over the surface S_o, results in:

$$\iint_{S_o} (\hat{n}\times\mathbf{T}) \bullet \mathbf{E}ds = -\iint_{S_o} (\hat{n}\times\mathbf{T}) \bullet (\nabla\times\mathbf{F})\,ds - j\omega\mu_o \iint_{S_o} (\hat{n}\times\mathbf{T}) \bullet \mathbf{A}ds$$
$$+ \frac{1}{j\omega\varepsilon_o}\iint_{S_o} (\hat{n}\times\mathbf{T}) \bullet (\nabla\nabla\bullet\mathbf{A})\,ds + \iint_{S_o} (\hat{n}\times\mathbf{T}) \bullet \mathbf{E}_{inc}ds \tag{17}$$

After some mathematical manipulations[7, pp.42], [8, pp.135], and substituting equations (8) and (9) in the above equation, it can be rewritten as:

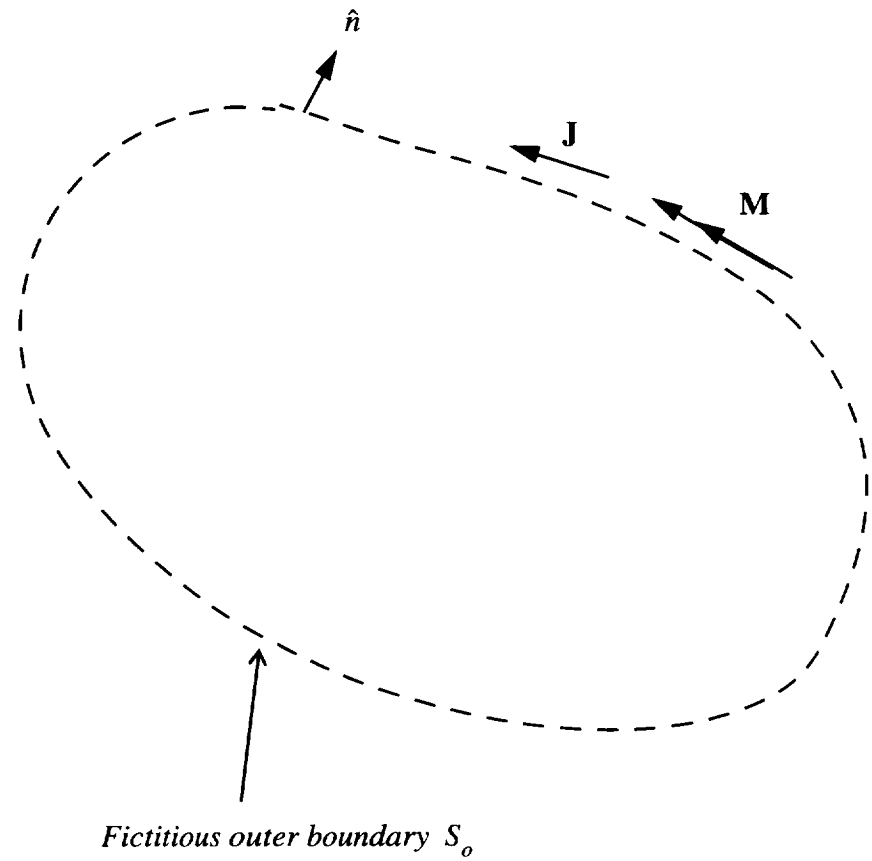

Figure 5 Equivalent current representation of the outer surface S_o

$$\frac{1}{2}\iint_{S_o} (\hat{n}\times\mathbf{T}) \bullet \mathbf{E}ds + \frac{1}{4\pi}\iint_{S_o} (\hat{n}\times\mathbf{T}) \bullet \left(\iint_{S_o} \mathbf{M}\times\nabla' G ds'\right) ds$$

$$+ \frac{j\omega\mu_o}{4\pi}\iint_{S_o} (\hat{n}\times\mathbf{T}) \bullet \left(\iint_{S_o} \mathbf{J} G ds'\right) ds + \frac{1}{j\omega\varepsilon_o(4\pi)}\iint_{S_o} \{\nabla\bullet(\hat{n}\times\mathbf{T})\}\ \{\iint_{S_o} (\nabla\bullet\mathbf{J})\, G ds'\}\, ds$$

$$= \iint_{S_o} (\hat{n}\times\mathbf{T}) \bullet \mathbf{E}_{inc} ds \qquad (18)$$

where $\iint$ indicates that the singular point has been removed and

$$G = \frac{\exp(-jk_o|\mathbf{r}-\mathbf{r}_o|)}{|\mathbf{r}-\mathbf{r}_o|} \qquad (19)$$

Equation (18) is written in a matrix form by choosing the proper basis functions for $\mathbf{M}$ and $\mathbf{J}$ and accordingly using the testing function $\hat{n}\times\mathbf{T}$. Within each surface triangle, the surface currents can be expressed as

$$\mathbf{M} = \mathbf{E}\times\hat{n} = -\sum_{i=1}^{3} e_i(\hat{n}\times\mathbf{W}_i) \qquad (20)$$

$$\mathbf{J} = \sum_{i=1}^{3} I_i(\hat{n}\times\mathbf{W}_i) \qquad (21)$$

and the testing function as

$$\hat{n}\times\mathbf{T} = \hat{n}\times\mathbf{W}_j \qquad j=1,2,3 \qquad (22)$$

In equation (20), e_i represents the same unknown coefficient as in equation (4) and in equation(21) I_i represents the unknown coefficient for the surface electric current densisty. In equations (20) and (21), it is interesting to note that, the vector edge basis functions $\mathbf{W}_i$, which are initially used for electric field are used to represent the surface current densities in the form of $\hat{n}\times\mathbf{W}_i$. The expansion functions $\mathbf{W}_i$ are used to build tangential continuity into the field representation. In contrast, the cross product of $\hat{n}$ with these functions results in another set of basis functions which guarantee normal continuity with zero curl and nonzero divergence and hence are ideally suited for representing surface current densities[2]. During the current investigation, it has been observed that the roof top basis functions for triangular pathes used by Rao[7] and the basis functions used here proved to be numerically identical to each other confirming the above point of view.

Equations (20-22) are substituted in equation (18) and integrated over all the triangular patch elements on surface S_o to obtain the following matrix equation:

$$\left[M_1\right]\{e\} + \left[M_2\right]\{I\} = \{b_1\} \tag{23}$$

where

$$\left[M_1\right] = \frac{1}{2}\iint_{S_o} (\hat{n}\times\mathbf{T}) \bullet \vec{E}ds + \frac{1}{4\pi}\iint_{S_o} (\hat{n}\times\mathbf{T}) \bullet \left(\iint_{S_o} \mathbf{M}\times\nabla' G ds'\right)ds \tag{24}$$

$$\left[M_2\right] = \frac{j\omega\mu_o}{4\pi}\iint_{S_o} (\hat{n}\times\mathbf{T}) \bullet \left(\iint_{S_o} \mathbf{J}Gds'\right)ds + \frac{1}{j\omega\varepsilon_o(4\pi)}\iint_{S_o} \{\nabla\bullet(\hat{n}\times\mathbf{T})\}\left\{\iint_{S_o} (\nabla\bullet\mathbf{J})\, Gds'\right\}ds \tag{25}$$

and

$$\{b_1\} = \iint_{S_o} (\hat{n}\times\mathbf{T}) \bullet \mathbf{E}_{inc}ds \tag{26}$$

The singularities in evaluating the integrals in equation (25) are handled analytically by using the closed form expressions given in[9].

Using Maxwell's equation $\nabla\times\mathbf{E} = -j\omega\mu_o\mu_r\mathbf{H}$, the surface integral on the right hand side of the equation (3) can be written as

$$-\iint_{S_o} \mathbf{T} \bullet \left(\hat{n}\times\frac{1}{\mu_r}\nabla\times\mathbf{E}\right)ds = \iint_{S_o} \mathbf{T} \bullet (\hat{n}\times\mathbf{H})\,ds \tag{27}$$

By equivalence principle, it can be noted that $\mathbf{J} = \hat{n}\times\mathbf{H}$ on the surface S_o. Substituting this into equation (27), equation (3) can be rewritten as:

$$\iiint_V \frac{1}{\mu_r}(\nabla\times\mathbf{T}) \bullet (\nabla\times\mathbf{E})\,dv - k_o^2\varepsilon_r\iiint_V \mathbf{T}\bullet\mathbf{E}dv = \iint_{S_o} \mathbf{T}\bullet\mathbf{J}ds \tag{28}$$

Substituting equations (4),(5) and (14) in the above equation and integrating over all the tetrahedral elements to evaluate the volume integrals on the left hand side and integrating over all the surface triangular elements to evaluate the surface integral on the right hand side, it can be written in a matrix form as

$$\left[F_1\right]\{e\} + \left[F_2\right]\{I\} = \{0\} \tag{29}$$

where

$$\left[F_1\right] = \iiint_V \frac{1}{\mu_r}(\nabla\times\mathbf{T}) \bullet (\nabla\times\mathbf{E})\, dv - k_o^2\varepsilon_r \iiint_V \mathbf{T} \bullet \mathbf{E}\, dv \tag{30}$$

$$\left[F_2\right] = \iint_{S_o} \mathbf{T} \bullet \mathbf{J}\, ds \tag{31}$$

and $\{0\}$ is the null vector. The evaluation of the volume integrals over a tetrahedral element is given in detail in [6].

Equations (23) and (29) are combined to form a system matrix equation:

$$\begin{bmatrix} F_1 & F_2 \\ M_1 & M_2 \end{bmatrix} \begin{bmatrix} e \\ I \end{bmatrix} = \begin{bmatrix} 0 \\ b_1 \end{bmatrix} \tag{32}$$

In the above system matrix F_1 and F_2 are sparse matrices and M_1 and M_2 are dense matrices and also the total matrix is complex and non-symmetric in nature. This matrix equation is solved using a diagonally preconditioned biconjugate gradient algorithm, where it is necessary to store only the non zero entries of the matrix.

The solution of equation (32), enables the computation of the electric field in the computational volume and the equivalent magentic and electric current densities on the surface terminating the computational domain. Using the equivalent electric and magnetic current densities on the surface terminating the computational domain, the scattered electric far field is computed as [5]

$$\mathbf{E}_{fscat}(\mathbf{r})\Big|_{r\to\infty} = -jk_o\eta_o \frac{\exp(-jk_o r)}{4\pi r} \iint (\hat{\theta}\hat{\theta} + \hat{\phi}\hat{\phi}) \bullet \mathbf{J}(x', y') \exp(jk_o \sin(\theta(x'\cos\phi + 'y\sin\phi) + z'\cos\theta))\, dx'dy'$$

$$+ jk_o \frac{\exp(-jk_o r)}{4\pi r} \iint (-\hat{\theta}\hat{\phi} + \hat{\phi}\hat{\theta}) \bullet \mathbf{M}(x', y') \exp(jk_o \sin(\theta(x'\cos\phi + 'y\sin\phi) + z'\cos\theta))\, dx'dy' \tag{33}$$

where (r, θ, ϕ) are the spherical coordinates of the observation point. The radar cross section is given by

$$\sigma = \lim_{r\to\infty} 4\pi r^2 \frac{\left|\mathbf{E}_{fscat}(\mathbf{r})\right|^2}{\left|\mathbf{E}_{inc}(\mathbf{r})\right|^2} \tag{34}$$

Appendix 2

Listing of the Distribution Disk

```
/FEMOM3DS-1.0

total 32
drwxr-xr-x  2 cjr          512 Jul 29 14:52 Example1/
drwxr-xr-x  2 cjr          512 Jul 29 14:51 Example2/
drwxr-xr-x  2 cjr         1024 Jul 29 14:52 FEMOM3DS/
drwxr-xr-x  2 cjr         1024 Jul 29 14:51 PRE_FEMOM3DS/

/FEMOM3DS-1.0/PRE_FEMOM3DS

total 528
-rw-r--r--  1 cjr         6712 Jul 29 14:46 cosmos2fem.f
-rw-r--r--  1 cjr         5358 Jul 28 14:30 edge.f
-rw-r--r--  1 cjr          624 Jun 10 15:47 makefile
-rw-r--r--  1 cjr         1651 Jul 28 14:27 meshin.f
-rw-r--r--  1 cjr         1715 Jun 10 14:41 param0
-rw-r--r--  1 cjr          800 Nov 15  1994 pmax.f
-rwxr-xr-x  1 cjr       472284 Jul 28 14:30 pre_femom3ds*
-rw-r--r--  1 cjr         7719 Jun 10 16:25 pre_femom3ds.f
-rw-r--r--  1 cjr         2798 Jun 10 15:46 surfel.f

/FEMOM3DS-1.0/FEMOM3DS

total 752
-rw-r--r--  1 cjr         5151 Jul 23 14:39 analy.f
-rw-r--r--  1 cjr         4583 Jul 23 14:39 basis.f
-rw-r--r--  1 cjr         4220 Jul 28 15:53 bicgdns.f
-rw-r--r--  1 cjr         2186 Jul 23 14:42 elembd.f
-rw-r--r--  1 cjr         3616 Jul 23 14:43 elmatr.f
-rw-r--r--  1 cjr         3026 Jul 23 14:44 excit.f
-rwxr-xr-x  1 cjr       529008 Jul 28 15:53 femom3ds*
-rw-r--r--  1 cjr        17609 Jul 28 15:25 femom3ds.f
-rw-r--r--  1 cjr         3028 Jul 23 14:44 fourierxy.f
-rw-r--r--  1 cjr          801 Jul 23 15:33 makefile
-rw-r--r--  1 cjr         1738 Jul 28 14:38 param
-rw-r--r--  1 cjr         1269 Jul 23 14:47 pleq.f
-rw-r--r--  1 cjr         5321 Jul 23 14:48 quadpts.f
-rw-r--r--  1 cjr         3410 Jul 23 14:48 scatter.f
-rw-r--r--  1 cjr          307 Nov 17  1994 second.f
-rw-r--r--  1 cjr         1826 Jul 23 14:48 triangeh.f
```

```
-rw-r--r--  1 cjr          3137 Jul 23 14:49 triangej.f
-rw-r--r--  1 cjr          3321 Jul 23 14:49 triangej0.f
-rw-r--r--  1 cjr          2681 Jul 23 14:50 triangej01.f
-rw-r--r--  1 cjr          3494 Jul 23 14:51 triangem.f
-rw-r--r--  1 cjr          2082 Jul 23 14:51 triangem0.f
-rw-r--r--  1 cjr          1572 Jul 23 14:51 unorm.f
-rw-r--r--  1 cjr           856 Jul 23 14:53 vcross.f
-rw-r--r--  1 cjr           768 Jul 23 14:53 vdot.f
-rw-r--r--  1 cjr          5028 Jul 23 14:54 zmatrixeh.f
-rw-r--r--  1 cjr          8817 Jul 23 15:46 zmatrixej.f
-rw-r--r--  1 cjr          7591 Jul 23 15:46 zmatrixem.f
```

/FEMOM3DS-1.0/Example1

```
total 192
-rw-r--r--  1 cjr            40 Jul 24 09:34 input
-rw-r--r--  1 cjr            22 Jul 23 15:05 sp.MAT
-rw-r--r--  1 cjr         10590 Jul 29 11:01 sp.MOD
-rw-r--r--  1 cjr          2051 Jul 29 11:04 sp.OUT
-rw-r--r--  1 cjr         19698 Jul 29 11:02 sp.PIN
-rw-r--r--  1 cjr           561 Jul 29 11:02 sp.POUT
-rw-r--r--  1 cjr           472 Jul 29 11:01 sp.SES
-rw-r--r--  1 cjr            80 Jul 29 11:04 sp_bicgd.DAT
-rw-r--r--  1 cjr         41054 Jul 29 11:02 sp_edges.DAT
-rw-r--r--  1 cjr         10873 Jul 29 11:02 sp_nodal.DAT
-rw-r--r--  1 cjr         38262 Jul 29 11:02 sp_surfed.DAT
```

/FEMOM3DS-1.0/Example2

```
total 264
-rw-r--r--  1 cjr            22 Jul 24 09:08 inlet.MAT
-rw-r--r--  1 cjr         20748 Jul 28 14:32 inlet.MOD
-rw-r--r--  1 cjr          2229 Jul 28 16:59 inlet.OUT
-rw-r--r--  1 cjr         38377 Jul 29 08:20 inlet.PIN
-rw-r--r--  1 cjr           561 Jul 29 08:20 inlet.POUT
-rw-r--r--  1 cjr           551 Jul 28 14:33 inlet.SES
-rw-r--r--  1 cjr          1520 Jul 28 16:59 inlet_bicgd.DAT
-rw-r--r--  1 cjr         74008 Jul 29 08:20 inlet_edges.DAT
-rw-r--r--  1 cjr         22352 Jul 29 08:20 inlet_nodal.DAT
-rw-r--r--  1 cjr         49110 Jul 29 08:20 inlet_surfed.DAT
-rw-r--r--  1 cjr            28 Jul 28 14:34 input
```

Appendix 3

Sample *.SES files of COSMOS/M

The geometry modelling and meshing can be accomplished by using COSMOS/M. A variety of commands are available to define geometries. The constructed geometry is meshed and the mesh data can be written to a file with the `Modinput` command. Dielectric materials are identified by using material property command before meshing the corresponding part of the dielectric material. These are used as indices to tetrahedral elements, which will correspond to an entry in the *problem*.MAT file. Specification of the surfaces which are perfectly conducting, surfaces forming the radiating aperture and the input plane is accomplished by enforcing pressure boundary conditions on respective surfaces. Before the pressure condition is specified, a load condition has to be defined to indicate what type of surface is being specified. Load conditions of 1, 2, and 3 corresponds to perfectly conducting surface, surface with equivalent electric current and surface with equivalent magnetic current, respectively.

The *.SES files for the sample runs presented in section 4 are given below.

Example 1:

```
C*
C*  COSMOS/M      Geostar V1.75
C*  Problem : sp          Date :  7-29-97  Time :  8:32:50
C*
PT 1 0.000000 0.000000 0.000000
PT 2 0.000000 0.000000 0.16
PT 3 0.16 0.000000 0.000000
CRCIRLE 1 1 2 3 0.160 90 1
CRCIRLE 2 1 2 4 0.160 90 1
SFSWEEP 1 2 1 X 360.000000 4
PH 1 SF 1 0.1 0.001000 1
SCALE 0.000000
PART 1 1 1
CLS 1
PARTPLOT 1 1 1
MA_PART 1 1 1 1 0 4
ACTSET LC 1
ACTSET LC 2
```

```
PSF 1 2 8 1 2 2 4
ACTSET LC 3
PSF 1 3 8 1 3 3 4
```

Example 2:

```
C*
C*  COSMOS/M      Geostar V1.75
C*  Problem : inlet            Date :  7-24-97  Time :  9:39: 5
C*
SF4CORD 1 -0.15 -0.15 -0.1 0.15 -0.15 -0.1 0.15 0.15 -0.1 -0.15
0.15 &
-0.1
PLANE Z 0 1
VIEW 0 0 1 0
SCALE 0
VLEXTR 1 1 1 Z 0.2
PLANE Z 0 1
VIEW 1 1 1 0
SCALE 0
PH 1 SF 1 0.08 0.0001 1
PART 1 1 1
MA_PART 1 1 1 1 0 4
NMERGE 1 101 1 0.0001 0 0 0
NCOMPRESS 1 101
CLS 1
CLS 1
CLS 1
ACTSET LC 1
PSF 1 1 1 1 1 1 4
PSF 3 1 6 1 1 1 4
ACTSET LC 2
PSF 1 2 6 1 2 2 4
ACTSET LC 3
PSF 2 3 2 1 3 3 4
```

Appendix 4

Generic Input file format for PRE_FEMOM3DS

The following is the format of the generic input file (`problem.PIN`) to be supplied to PRE_FEMOM3DS with required nodal data.

N_n N_e N_p N_{a1} N_{a2} N_g	● N_n: Number of nodes ● N_e : Number of trahedral elements ● N_p : Number of triangular elemets on PEC surfaces ● N_{a1} : Number of triangular elements on surface with equivalent electric current ● N_{a2} : Number of triangular elements on surface with equivalent magnetic current ● N_g : Maximum number of material groups
x_1, y_1, z_1 x_2, y_2, z_2 . . . . . $x_{N_p}, y_{N_p}, z_{N_p}$	Coordinates of the nodes 1,2,3...,N_n
$n_{11}, n_{21}, n_{31}, n_{41}, mg(1)$ $n_{12}, n_{22}, n_{32}, n_{42}, mg(2)$ $n_{1N_e}, n_{2N_e}, n_{3N_e}, n_{4N_e}, mg(N_e)$	Node numbers connecting each tetrahedral element 1, 2, 3, ...,N_e, and material group index number for each element

N_{e1} , n_{11}, n_{21}, n_{31} N_{e2} , n_{12}, n_{22}, n_{32} . . . N_{eN_p}, $n_{1N_p}, n_{2N_p}, n_{3N_p}$	Global number of the terahedral element with a triangular face on PEC surface ($N_{e1}, N_{e2}, \ldots\ldots, N_{eN_p}$) and three nodes connecting the triangular element
N_{e1}, n_{11}, n_{21}, n_{31} N_{e2}, n_{12}, n_{22}, n_{32} . . . . $N_{eN_{a1}}, n_{1N_{a1}}, n_{2N_{a1}}, n_{3N_{a1}}$	Global number of the terahedral element with a triangular face on the electric current surface ($N_{e1}, N_{e2}, \ldots\ldots, N_{eN_{a1}}$) and three nodes connecting the triangular element
N_{e1} , n_{11}, n_{21}, n_{31} N_{e2}, n_{12}, n_{22}, n_{32} . . . . . $N_{eN_{a2}}, n_{1N_{a2}}, n_{2N_{a2}}, n_{3N_{a2}}$	Global number of the terahedral element with a triangular face on the magnetic current surface ($N_{e1}, N_{e2}, \ldots\ldots, N_{eN_{a2}}$) and three nodes connecting the triangular element

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FEMOM3DS is a computer code written in FORTRAN 77 to compute electromagnetic(EM) scattering characteristics of a three dimensional object with complex materials using combined Finite Element Method (FEM)/Method of Moments (MoM) technique. This code uses the tetrahedral elements, with vector edge basis functions for FEM in the volume of the cavity and the triangular elements with the basis functions similar to that described for MoM at the outer boundary. By virtue of FEM, this code can handle any arbitrarily shaped three-dimensional cavities filled with inhomogeneous lossy materials. The User's Manual is written to make the user acquainted with the operation of the code. The user is assumed to be familiar with the FORTRAN 77 language and the operating environment of the computers on which the code is intended to run.

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